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PROGRESS IN PULSED POWER FUSION*

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Abstract

Pulsed power offers an efficient, high energy, economical source of x-rays for inertial confinement fusion (ICF) research. We are pursuing two main approaches to ICF driven with pulsed power accelerators: intense light ion beams and z-pinches. This paper describes recent progress in each approach and plans for future development.

Introduction

The United States Department of Energy has been funding research into Inertial Confinement Fusion since early 1970s. The long term goal of this ICF research is the production of high yield in the laboratory for Defense and Energy applications. High yield in this context means thermonuclear yield of 200-1000 MJ. Recently the Department has selected the laser technology to demonstrate ignition in the laboratory. The National Ignition Facility is a project in the United States aimed at building a large laser capable of delivering 1.8 MJ of 3ω (350 nm) light to a target. The 1.8 MJ of laser energy will result in ~ 100 - 150 kJ of x-ray energy absorbed in the capsule. The predicted thermonuclear yield with this absorbed x-ray energy is 2 - 20 MJ. Ignition demonstration in the NIF would be a major step forward toward obtaining high yield in the laboratory. However, a high-yield target is expected to require approximately 1 MJ of x-rays absorbed in the capsule ablator with radiation symmetry on the surface of the capsule of better than 1%. In order to achieve this radiation symmetry, a large case-to-capsule radius ratio is needed. Consequently, a driver will be required with approximately 10 MJ incident on the target, prohibitively expensive using laser technology. In addition, any energy application of ICF will require a repetitive pulse capability (4 Hz); again, not possible with lasers. Pulsed-power-driven ICF offers an attractive alternative with affordable, high energy, high efficiency drivers and the potential for repetitive pulse operation. The pulsed power ICF program has two main elements: intense light ion beams and z-pinches. This paper provides an overview of recent progress in both of these pulsed power approaches as well as our plans for the future.

Progress in Light Ion Beam Development

The baseline approach for a light-ion beam-driven high-yield capability (HYC), also called the Laboratory Microfusion Facility (LMF) includes 12 low-power ion beams with an on-target

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ion power of 5.4 TW each and 12 high-power beams (~ 50 TW each). For a recent review article on light ion ICF with extensive references see reference [1]. Each high power module would produce a 27 TW lithium beam at voltages ranging from 28 - 35 MV controlled so as to bunch the beam and increase the beam power by a factor of ~ 2 as it travels from the diode to the target, resulting in a ~ 50 TW beam at the target location. The required focal intensity is somewhat in excess of 50 TW/cm^2. Lithium ion beams have been focused on the Particle Beam Fusion Accelerator II (PBFA II) to intensities of 2 TW/cm^2. The resulting specific deposition in an ion-driven hohlraum was 1400 TW/g [2]. This represents the highest specific power deposition created by an ion beam. The achievement of a 2 TW/cm^2 focal intensity was an improvement of over an order of magnitude in intensity between the period of 1990 through 1993. However, this rapid increase in focal intensity has been difficult to continue.

The available power brightness (I) from a focused ion beam is determined principally by the beam microdivergence ($\Delta\theta$) and the lithium beam power (P_i) available ($I \propto P_i/\Delta\theta^2$). Progress in understanding and reducing divergence has resulted in lithium beam microdivergence on PBFA II of 20 - 25 mrad. High yield facility microdivergence requirements depend on the mode of transport considered but will be between 6 and 12 mrad. Further improvement in beam divergence will likely rely upon improvements in source divergence, source uniformity, control of electromagnetic instabilities, and two-stage acceleration in which the ion longitudinal momentum is increased while maintaining the transverse momentum imparted in the first stage of acceleration.

Lithium ion power available has been shown, through a series of carefully diagnosed experiments, to be limited by an unwanted ion current flowing in parallel with the desired lithium beam. This parallel current (parallel load) has been designated the parasitic load. The parasitic load is composed of accelerated ions from the bulk and surface contamination in the ion source and surrounding hardware. Recently on the SABRE accelerator [3], through an extensive protocol of RF glow discharge cleaning and heating of the anode-cathode gap and impermeable anode coatings, the peak lithium current density was increased by a factor of 50-100%.

A major effort since Beams '94 has been the design, construction, and implementation of an extraction ion diode of PBFA II. PBFA II recently completed its 10th year of operation, and until late last year, the ion diode on PBFA II was a radially focusing diode in which the ion beam was focused to the cylindrical axis at the midplane of the accelerator. All high-yield facility concepts utilizing light ion beams require that the beam be extracted from the diode region and propagated several meters to the target. The modification to PBFA to allow for extraction-ion-diode experiments has been named PBFA-X (Fig. 1). The first shot of PBFA-X with an ion beam was taken in September of 1995. In its first experimental series completed in April of 1996, PBFA-X demonstrated a much higher shot rate than achieved with the radial diode. The improved diagnostic access and proximity of vacuum pumping with this hardware were also advantages.

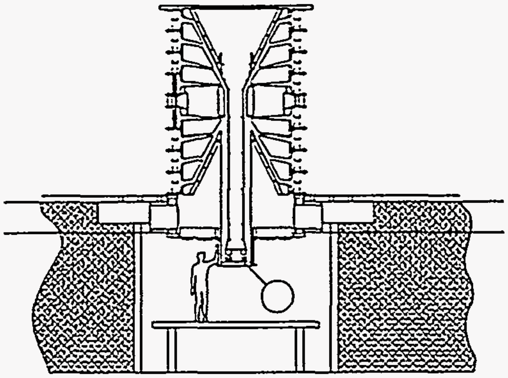
Fig. 1. PBFA-X configuration

With the success of the heating and cleaning experiments on SABRE, an improved protocol was applied to the PBFA-X extraction diode resulting in a dramatic improvement in the diode voltage history. A prematurely shortened voltage pulse is a signature of a falling diode impedance due to dramatically increasing total ion current in the diode. This total ion current is composed of both the desired lithium current and the parasitic current. By application of heating and cleaning techniques on PBFA-X, the diode pulse width was greatly increased. The addition of an active ion source then resulted in a lithium ion power extracted from the diode of ~ 4 TW, the most ever from an extraction ion diode.

This advance in intense ion beam generation and focusing has resulted from careful application of multiple diagnostics, analytic theory, and numerical simulation. As an example of diagnostic improvements, it is now possible to measure on a millimeter spatial scale with nanosecond time resolution, electric fields in excess of 10 MV/cm using visible spectroscopy to measure the Stark shift [4]. Analytic theory, coupled with numerical simulation, has resulted in the ability to rapidly optimize magnetic field profiles for desired ion-beam current-density profile, an effort which in the past has taken about one week of experimentation for each different diode configuration [5].

Once an ion beam with adequate microdivergence and power is achieved, it still must be transported from the diode approximately 4 m to the target in any high-yield facility. This standoff is required to protect the beam generation apparatus from the debris and energy resulting from a high yield explosion, and to provide a drift distance for voltage-ramped pulse compression. Progress in transport physics has also been impressive. Previously, calculations using the IPROP code [6] have been shown to give excellent agreement with gas breakdown transport experiments at the Naval Research Laboratory (NRL) [7]. IPROP now predicts excellent current neutralization (at ~ 1 torr) for the achromatic lens transport system and substantial net currents (up to 50%) for the self-pinched mode of propagation (at ≤ 100 mtorr). The baseline approach for a light ion LMF uses the achromatic lens system in which a solenoidal lens is located about 1.5 m from the target; results from the University of Wisconsin show that this is workable for LMF, and even for the LIBRA-LITE power plant concept. However, a more desirable approach is to use self-pinched transport which allows the beam to propagate several meters in gas to the target. Recent IPROP simulations for self-pinched transport are very encouraging. Self-pinched transport experiments have been initiated at NRL using 1 MeV protons, and will be initiated this summer at Sandia National Laboratories using 4 MeV Li ions. Self-pinched transport is very attractive for both high yield and energy options for both light and heavy ions.

Although advances in understanding of the physics of light ion beam generation and focusing have been impressive, the maximum Li intensity has remained at 2 TW/cm^2 since 1993 while research continued on the separate issues of divergence and parasitic load reduction. Because of the outstanding results recently obtained with pulsed power driven z-pinches described in the next section, the near term emphasis in the pulsed power ICF program is shifting away from light ion beams towards z-pinches. Basic research into the fundamental issues limiting light ion beam focusing will be accomplished on the smaller SABRE accelerator at Sandia, on the Gamble II accelerator at the Naval Research Laboratory, and on the recently completed COBRA accelerator at Cornell. We anticipate that progress during the next two years will justify a second experimental series at the much high power levels available on PBFA-X.

Progress in Z-pinch Development

Pulsed power accelerators have been used for many years to drive magnetic implosions (z-pinches). The load in these implosions has varied from cylindrical arrays of wires arranged at constant radius, to gas puffs and low density foams. These loads have historically coupled extremely well to pulsed power accelerators with resulting high electrical-to-kinetic energy efficiency. In the application as an x-ray source, the kinetic energy in the imploding system is converted into x-rays when the imploding plasma stagnates on axis. Z-pinches have historically been efficient at coupling electrical energy into kinetic energy in the implosion system, but the x-ray power available from these z-pinches has been limited to less than 20 TW. During the past year, however, breakthroughs in load fabrication (which has allowed in excess of 190 5 μg/cm Al and W wires to be mounted forming a 1 - 2 cm diameter cylindrical array) and improved understanding of load behavior have resulted in dramatic improvements in x-ray power available from these sources (see [8] and [9] for results and references). Recently the x-ray power available from a tungsten load has exceeded 85 TW, the most power ever generated in a laboratory device. Remarkably, the energy in x-rays has remained nearly constant at 400 - 500 kJ as the power has been increased. These results were obtained on the Saturn accelerator. Saturn delivers 20 TW of electrical power to the load. Therefore, the 85 TW in x-rays represents a factor of four power gain. Such high power and energy x-rays sources have major applications in the ICF program.

Experiments have been performed utilizing these x-ray sources to heat vacuum hohlraums [2]. These hohlraums are complementary to those generated by lasers and offer unique capability in large volumes (5 cm^3) and long life time (>20 ns) at moderate temperatures (>80 eV). These large, long lived hohlraums provide an excellent environment for many different experiments relevant to both ignition and high yield capsule designs. For example, smaller, secondary hohlraums can be mounted on the side of the primary hohlraum (Fig. 2) to simultaneously measure secondary hohlraum drive conditions while performing experiments in which shock waves are driven through samples of ablator materials mounted to the other secondary hohlraum. Besides providing a source of x-rays to study ignition relevant physics, these z-pinches can be used to provide x-rays to drive ICF capsules themselves. Several concepts employing vacuum hohlraums or imploding hohlraums (hohlraums in which the hohlraum case itself implodes thereby increasing the hohlraum temperature) have been investigated with computer modeling. Experiments to explore these concepts have just begun [2, 10].

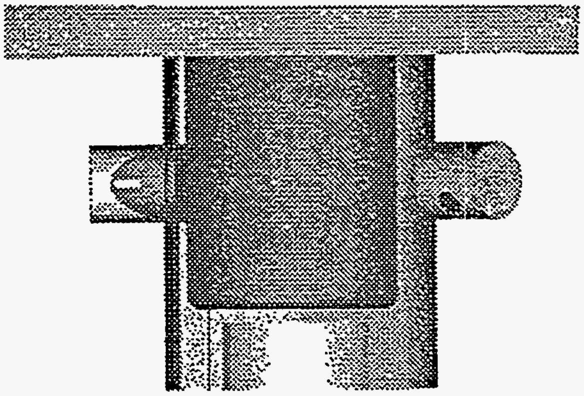

Fig. 2. Z-pinch driven hohlraum experimental configuration: primary hohlraum with secondary hohlraums

A major modification to PBFA to enable z-pinch experiments is underway (PBFA-Z). The Saturn accelerator delivers approximately 7 MA to a z-pinch load resulting in approximately 500 kJ of x-rays being generated. PBFA-Z when used to drive z-pinches will generate approximately 18 MA through a z-pinch load and will result in the production of 1.5 - 2 MJ of x-rays. The 85 TW and >80 eV produced on Saturn are expected to scale to >150 TW of x-rays and >120 eV in vacuum hohlraums on PBFA-Z. If this scaling can be demonstrated in experiments beginning later this summer, then the way will be clear to the follow on proposed accelerator, X-1, which would be designed to deliver 40 MA to a z-pinch load generating 6 - 8 MJ of x-rays.

Conclusions

Pulsed Power provides an economical source of x-ray energy for ICF research. In the near term we plan to use energetic, intense z-pinch x-ray sources for ignition-relevant and high-yield capsule physics experiments. Capsule implosions driven by these x-ray sources have been simulated using coupled radiation/hydrodynamics computer codes and indications are that they are worth pursuing with existing and future pulsed-power accelerators. Z-pinches represent the best means to generate high-energy, high-power x-ray environments for exploring ignition and high-yield relevant capsule physics in the near term. In the far term, light-ion driven ICF will be required for repetitive high yield applications such as energy production. Our plan, therefore, is to utilize z-pinches in the near term to explore and refine the high-yield capsule designs and requirements, while in parallel developing intense ion-beam technology so that, when high yield is demonstrated in the laboratory, technology for utilizing the high-yield capability for defense applications and energy production will be available.

Acknowledgments

The pulsed power ICF program is an international effort. Important contributions to the field are being made by scientists and engineers from around the world. This presentation has emphasized activities at Sandia National Laboratories, however, the authors would like to acknowledge our many colleagues who have contributed to the recent progress. Many of these advances are presented elsewhere at this conference.

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